

## CONTROL OF THIN FILM MATERIALS PROPERTIES USED IN HIGH DENSITY MULTICHIP INTERCONNECT

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### ABSTRACT

Most literature on High Density Multichip Interconnect (HDMI) focuses almost exclusively on processing of the organic dielectric. Nevertheless, it is only one of the components in High Density Multichip Modules.

Substrate properties, metal dielectric adhesion, internal stresses in the various films, and many other physico-chemical properties of the materials, can all be affected by neighbouring layers or process parameters improperly identified. Thus, in the course of process development, the real causes of difficulties and observed phenomena can easily be misconstrued.

This paper reviews some of the relationships between the properties of the thin film metallization and their effects on the dielectric layers. It also points out to some of the difficulties that can occur when treating the dielectric and the metallic layers as separate issues.

### INTRODUCTION

The need to improve the current packaging and interconnect technologies has renewed the interest in using polymers as a dielectric layers between thin film interconnect conductor lines [1-3]. Uses include traditionally high reliability oriented military and space applications [4-5].

Polymers are currently necessary for the fabrication of the smallest electronic miniaturized structures [6] with matched impedance interconnect conductor lines [7]. The impedance of transmission lines is largely controlled by the ratio of line width to dielectric thickness. Multichip modules, most commonly, have three basic type of transmission lines as shown in figure 1.

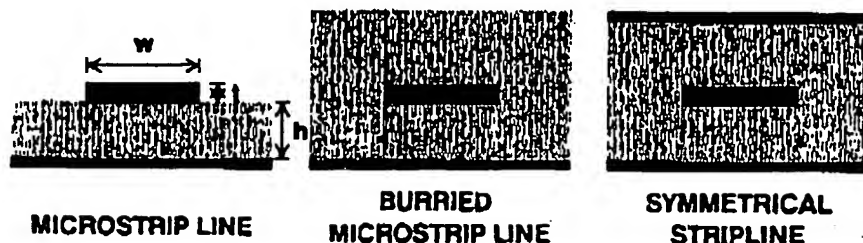


Figure 1 - Basic Configurations of Transmission Lines.

Other transmission structures are possible, however the impedance of all line types involves control of the line width to materials thicknesses aspect ratio [8]. Inorganic dielectrics do not allow the fabrication of favorable aspects ratios providing both matched impedances and low resistive losses simultaneously. Low dielectric constant inorganic materials cannot be successfully and economically deposited in layers much over one micron thick, largely due to internal stresses related problems. Furthermore, inorganic materials have much higher dielectric constants than most available organic materials. The low resistive losses are obtained by using thicker metallization than used in semiconductor fabrication and shortening the path between chips relative to other methods of interconnect. Thicker metallization is impractical in IC work because of the difficulties it creates for the photolithography.

Several classes of organic dielectrics can remedy the deficiencies of inorganic materials for interconnection applications. Typical properties of both organic and inorganic materials are shown in Table 1.

STATUS OF AVAILABLE DIELECTRICS FOR MCM USE

	THERMAL SiO <sub>2</sub>	P or B SiO <sub>2</sub>	Si <sub>3</sub> N <sub>4</sub> PECVD	Si <sub>3</sub> N <sub>4</sub> PECVD	POLYIMIDE	ENHANCED POLYIMIDE	PFO	ECB	PPK
DIELECTRIC CONSTANT	F	F	P	F	G	VG	F	E	E
PLANARIZATION	P	F	P	P	G	VG	VG	E	P
THERMAL CYCLING RELIABILITY	G	G	G	G	VG	VG	VG	VG	F
DEFECT DENSITY	F	F	G	G	G	G	G	VG	E
THICKNESS RANGE	P	P	P	P	G	VG	VG	VG	E
PATTERNING PROCESS	VG	VG	G	G	VG	VG	VG	VG	P
DEFECT DENSITY	G	G	G	G	VG	VG	VG	VG	E
SUITABILITY FOR MCM	P	P	P	P	VG	E	E	E	E

TABLE 1 - Dielectric Properties of Potential Materials which can be considered for Interconnect Work.

Choosing a dielectric is the first step in building reliable High Density Multilayer Interconnect (HDMI) structures. Many others material related choices are necessary. An analysis of the potential interactions between the substrate and the various layers as well as interlayer interferences must be considered. A thorough understanding of each process steps is necessary. Assuming that the structures can be built, acceptable yields and long term reliability are attained only if all physical and chemical interactions of the layers are clearly understood.

One or two layers can be done, even with a marginal process which may not, however, allow to identify longer term reliability problems.

This paper examines some of the substrate and thin film properties and process criteria as it relates to the interaction between complex multilayer metal-polymer structures.

Specifics of polymers properties and processing recipes have been intentionally left out of this discussion. Indeed, the subject has often been reviewed in the literature and in manufacturers data sheets since the late 1960's [8-11].

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## ADHESION OF FILMS

In an HDML structure, the different layers offer several types of interfaces which must have controlled adhesive properties. The order in which the deposition occurs is just as important as the materials components of the structure.

Many studies of the substrate to metal or substrate to polymer adhesion characteristics have been made. Yet, the distinction between metal to polymer and polymer to metal interfaces is not always evident or even perceived as being different. Other types of interfaces, such as polymers to oxides, and polymer to polymer exist in a multichip module and are equally important.

Adhesion can be depending on physical factors such as the surface finish of an interface. However, the surface chemistry usually has a predominant role in reliable adhesion of films.

In the case of metal deposition on a polymer, the adhesion mechanism is usually based on a sharing of oxygen atoms between the metal and the polymer, as it would be the case with many metals deposited on an oxide [12].

Van der Waal forces, the presence of dipoles at the interface and the formation of interdiffusion layers, all contribute to good adhesion.

Most metals commonly used as adhesion layer in standard thin film work, usually exhibit good adhesion to fully cured polymers. Sometimes, sputter etching or plasma etching has been advocated to enhance adhesion. Note, that a reactive metal layer is not always necessary to obtain good adhesion with copper over polymers, as would be the case with copper over an oxide substrate. Good choices of underlayer would be chrome, nickel, aluminum, titanium, tantalum, etc., if the internal stresses in these films can be controlled. Stresses imparted to the polymer by the metal own internal stress will be described later.

Chemical interaction can also occur between a polyimide spun over metals such as copper or aluminum. Limited interdiffusion of copper into some polyimides has been observed at elevated temperature [13] which enhances the adhesion.

Stresses in the polyimide come from the volume reduction occurring in the B-staging or curing of the polymer and from differences in coefficient of expansion.

Special care must be taken to avoid problems with metals easily corroded such as copper. Polymers can desorb solvents during B-staging. Water which can corrode the underlaying metal is formed during imidization. See figure 2. The water formation appears as superheated steam due to the curing temperature. The steam forms copper oxides which have poor adhesion to the source metal. The corrosion rate is further accelerated by the relatively high temperatures sustained after the initial oxide formation throughout curing.

The situation is different when a metal is deposited over a fully cured and dehydrated polymer [14]. Adhesion of copper directly over polyimide can exceed 6000 psi in tensile strength at normal angle pull.

In most cases, it is preferable to deposit an intermediate adhesion metal between the polymer and the thin film copper to prevent copper migration. The copper migrates into the polymer by interdiffusion resulting from exposure of the interconnect to elevated temperature during fabrication or during the life of the products. It is feasible to deposit polyimide directly onto copper with proper processing steps while providing adequate direct adhesion to the copper and reasonable corrosion resistance.

The adhesion of polymer to polymer, and polymer to oxides has been extensively covered in relation to conventional semi-conductor applications where it has been used as passivation layer, alpha particules protection, or as insulation between metallization layers. Good adhesion of the polymers often relies on adhesion promoting treatment.

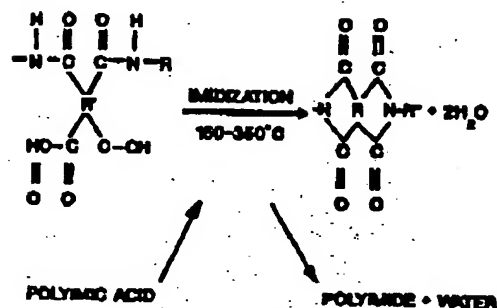


Figure 2 - Superheated Water is Formed During Curing of Polyimides.

Aluminum oxides, obtained from organo-metallic materials [15] or organo-silanes [16-17], are often used, and in some cases can be effective with metals as well.

#### STRESSES IN THIN FILMS

The quality of adhesion between layers can easily be weakened by internal stresses. Stresses can originate in the way a layer is formed or can be imparted by an adjacent film.

The fact that there is adhesion between two films, implies that the internal forces created by the stresses in the films, do not exceed the shear modulus of the interface, otherwise the films would peel off.

Due to their microstructure, thin films are seldom free from internal stresses if deposited without special precautions. Controlled deposition parameters can give so-called stress-free films.

Stresses can easily reach values beyond the modulus of rupture of many substrate materials, such as silicon crystal, if the interface adhesion is strong enough and does not break first.

In general, thin films can have tensile and rupture moduli beyond the values reported for bulk materials. They can be subjected to stresses causing creep and plastic deformation with yield values as high as 200 times bulk values. It should be emphasized that properties of thin films are usually substantially different from the materials in bulk form and are furthermore dependent on the deposition method. [18].

The internal stresses of a thin film can cause the substrate to deform. A mathematical model for the case of a single film on a substrate was described by Stoney [19] in the early part of this century and is still widely used. A recent general solution for multiple layers shows that the stresses in each individual layer can be linearly superposed, allowing to calculate the substrate deformation [20]. This multilayer stress model applies to most situations in HDMI fabrication. Evidently, stresses in any one thin film cannot exceed the modulus of rupture of any of the other films if the structure is to stay together. Forces must be transmitted through each layer to enable the linear superposition.

The strain exerted on any of the films must also stay within the elastic range if the film is to remain useful as an interlayer dielectric. Permanent deformation will result if a metal film has internal stresses exceeding its elastic range. See figure 3. In this case, plastic flow occurs and the polymer creases and ripples. With larger stresses, cracks will form when the elastic range is exceeded. See figure 4. Because of the linear superposition of stresses, problems can be compounded as the number of layers increases.



Figure 3 - Polyimide film subjected to compressive forces by metal layer which has been removed afterwards.

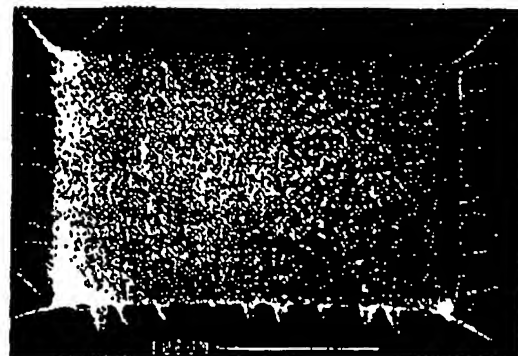


Figure 4 - Polyimide film subjected to tensile forces by a metal film, later removed. The polymer cracked.

Evaporated thin films as deposited have long been recognized to be stressed near their yield strength [21]. The stresses of these coatings appear to be independent of film thickness. Factors such as impurities in the film can introduce a tensile component [22]. Angle of incidence of the evaporant onto the substrate can modify the structure and stresses of the film. These factors were extensively studied for stress in the 60's, mainly for structure sensitive applications like deposition of soft ferro-magnetic films. Prior to this, not much has been done to control stresses in microelectronic conductors until the recent use of submicron lines. Stresses were not often recognized as contributing to problems, such as electromigration.

In the case of sputtered materials, it is difficult to generalize because of the variety of the sputtering deposition systems configuration and deposition parameters. Sputtering can be obtained by widely differing methods with various results. For instance, a planar diode sputtering configuration [23] cannot be expected to yield films similar to those produced from a sputter gun magnetron source [24] or a planar magnetron diode set-up [25] because of the dissimilarities in the thermodynamics of film formation.

In general, stresses in thin films are strongly dependent on their morphology, which in turn depends on the thermodynamic of the deposition conditions within the first few monolayers of the film under deposition. It may be pointed out that the average temperature measured on the back of a substrate should not be confused with the surface temperature prevailing at the molecular level in the upper few monolayers. The two temperatures can be vastly different. The surface temperature is extremely difficult to monitor directly. The thermal environment of the substrate is influenced by the fixturing of the substrate, the cooling or heating of the substrate holders, the plasma density, the electron flow, the bias voltage or plasma confinement among other factors. Thermodynamics have been recognized for some time to strongly influence the film morphology [26-27].

Films can be placed in compression or in tension or have no internal net stress for some particular range of deposition parameters. For a given result, the sputtering conditions are system dependant and are not necessarily easy to transpose from one system to another.

In many films, such as aluminum, stresses can be related to the grain structure. This is difficult to observe directly in many other films such as Ti, Ni, Mo, Ta, Cr or Ti-W because of the grain size. As for evaporated films, stresses in sputtering are sensitive to angle of incidence [28]. The sputtering gases have also been reported to influence film stresses [29], as well as the residual gases during deposition [30] and the amount of entrapped gases [31]. The large array of potential sputtering conditions variables may appear to be confusing and possibly unmanageable.

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Nevertheless, a system can be successfully and repeatably operated, once suitable parameters are experimentally found.

A very useful and direct method of stress control in sputtering is the application of a bias voltage to the substrate during deposition. This helps the film to restructure by re-sputtering weaker bonded adatoms from the substrate. A zero stress bias point can be found for many materials [32].

A related technique can be applied to evaporation which is then named ion plating [33]. This technique has been used with aluminum for many years.

In many sputtering systems, the application of a bias voltage may remain ineffective because of secondary parasitic discharges, preventing the bias voltage from being applied correctly to the substrate. The secondary discharges often go undetected because of the low bias power involved.

Experimentation should quickly determine the effectiveness of the bias by depositing material on thin flat substrates and next, by monitoring the substrate curvature imparted by stresses. A variety of stress measurement techniques can be used, depending on the accuracy required. The quickest method for qualitative measurements is to optically monitor the deformation of selected flat substrates with a light interferometer. Optically monitoring the distortion of a square grid reflection can be used for qualitative results. Bow measurements with a profilometer, X-ray diffraction, collimated light projected onto the deformed substrate [34] or beam bending techniques can also be effective methods depending upon the equipment available, the circumstances and the accuracy required.

#### METAL FILM MORPHOLOGY FOR HDMI

Stresses are largely a consequence of a film internal structure. As deposited, films can be amorphous or poly-crystalline with a variety of crystallite size and orientation. Although electrical bias or heat can influence the morphology of a film, other factors can influence the film structure, for example, residual gases, sputtering pressures [35] and film impurities. Very high deposition rates can give large grain size or even columnar structures [36]. In practice, stresses are mainly controlled by biasing. Low or zero stress films are attainable with moderate efforts in an appropriately configured sputtering system.

On polymers, the effective deposition rate is limited by the heat resistance of the polymer. The heat loads resulting from sputtering can be considerable at rates upward of one micron per minute. With sufficient sputtering power, surface temperature beyond 500 C are readily obtainable which will permanently damage any polymer. Aluminum and copper are of interest for HDMI fabrication. Copper deposition tends to apply a heavier heat load to the substrate than aluminum and is therefore less forgiving.

The substrate has a role to play in distributing or transferring the heat load to its holder [37]. If the heat conduction and the heat capacity of two substrates are significantly different, very different morphology can result, although the sputtering parameters are kept constant. This is very noticeable for thicker films [38].

Aluminum metallization is attractive because it allows to obtain films with good adhesion without underlayer. Aluminum is a very reactive material with oxygen or nitrogen. It readily adheres to most polymers and substrates by acting as an oxygen getter, therefore sharing oxygen bonds at its substrate interface. By the same token, its overall reactivity makes it sensitive to deposition chambers residual gases such as oxygen, nitrogen, or water vapor.

Stresses in aluminum can be high, if steps are not taken to control them. Small grained films obtained by deposition on cold substrates can be highly stressed, forming large isolated hillocks and voids.

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structure in the film [39]. Hillocks tend to be more abundant as the thickness of the film increases. It is therefore important to control thicker films requirements in high density multilayer interconnect demand metallization thicknesses significantly higher than for semiconductor work.

Hillocks are an expression of stress relief in aluminum. Because of the malleability of aluminum, plastic flow can be readily induced by compressional stresses from internal or external sources. Hillocks in thin films have been shown to be based on grain boundaries slippage and diffusion creep. Aluminum metallization is also susceptible to electro transport phenomena limiting its effective current carrying capacity in devices to a third of the copper capabilities. Electromigration is the motion of atoms, caused by a high density current. Electrons and holes exert a force on stationary atoms by momentum exchange. If the force is large enough, the atoms can move and electro transport phenomena take place at high current densities.

Effectively, electromigration is often a small practical concern for HDMI work due to the use of thicker films and wide traces compared to IC.

#### CONCLUSION

The fabrication of High Density Multilayer Interconnect (HDMI) relies on experience acquired in the semiconductor industry. However, many aspects are unique to the HDMI technology. In particular, the metal and polymer thicknesses are substantially higher than the ones used in semiconductor work in order to improve the characteristics of the interconnect.

Thin films in semi-conductors or hybrids are most often deposited on inorganic materials with high modulus of elasticity. In HDMI technology, the presence of thick polymers and metallic films thicker than usual create challenges of their own. It has been shown that control of adhesion between thin films and control of internal stresses are particularly critical because of the disparity of Young's modulus between metals and polymers. The individual components of a multilayer interconnect structure cannot be treated independently for process control purpose, due to the strong mechanical and chemical interactions which exists between layers.

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